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How much did we lose? Investigating the impact of depositional environments on bone artifact preservation: Preliminary taphonomical findings

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ABSTRACT

The impact of the depositional environment on bone artifacts is a crucial aspect of traceological research related to prehistoric osseous tools. The conditions in which bone artifacts are deposited significantly influence their preservation and the visibility of manufacturing and use-wear traces. Various factors such as soil composition, climate, burial depth, microbial activity and taphonomic processes (e.g., scavenging, water transport, and plant roots), can alter the state of bone artifacts. These processes may introduce additional wear or modify existing traces. This study presents the preliminary results of a taphonomical research examining the impact of different soils and post-depositional changes (mainly plant roots and fungi) on the preservation and visibility of cultural modifications on bones. Thus, an experiment was conducted where specially prepared modern bone pieces with various manufacturing traces on their surfaces were deposited outdoors in five types of soil for periods of 3 and 6 years. The study's findings provide numerous interesting observations and insights into the preservation of various types of manufacturing stigmata and the bones themselves, emphasizing the need for further in-depth research in this field. Furthermore, the presented findings may be helpful in taphonomic, traceological and forensic science research.

1. Introduction

Bone artifacts, are among the most valuable and unique expressions of prehistoric material culture. These objects were used for various purposes playing a role in nearly every aspect of ancient life. Bone artifacts served as basic materials for tools and hunting weapons (e.g., David, 2004; Langley, 2016) and held significant social and spiritual importance in prehistoric communities (Osipowicz et al., 2017, 2020; Falci et al., 2019). Artifacts made from osseous materials can provide valuable insights into ancient societies yet present considerable analytical challenges. Several key factors must be considered, such as the properties of the raw material itself, which vary depending on its type (bone or antler), the species of animal it originated from, and even its position within the skeleton (Jaczewski 1992, 61-81; Krysiak et al., 2011, pp. 29-37; Aerssens et al., 1998; Chen et al., 2009). Unfortunately, bone transforms quickly due to its physical and mechanical properties. Post-depositional processes can significantly impact the analysis of prehistoric bone artifacts, sometimes making planned research impossible. The literature often emphasizes the importance of secondary factors that can significantly affect the preservation of these materials and their impact on observed manufacturing and use-wear traces (e.g., Buc and Loponte, 2007; Vercoutère et al., 2007; Alvarez et al., 2014). Years of research on taphonomy and bone degradation have well-characterized the destruction of osseous materials in the literature (e.g., Fisher 1995; Fernández-Jalvo & Andrews, 2016). The impact of the depositional environment on bone artifacts is crucial in traceological research on prehistoric tools. The conditions of deposition can significantly influence their preservation and the visibility of manufacturing or functional traces.

The surface modifications can occur due to mechanical and chemical factors. Mechanical alteration involves physical changes in the bone tissue caused by direct action from an external agent without changing its composition. This can occur for various reasons, such as the exposure to weathering when remains are on the surface, the physical action of trampling, flowing water, animal or plant agents, or treatment processes during and after excavation (Shipman, 1981; Olsen & Shipman, 1988; Gaudzinski-Windheuser et al., 2010; Gümrükçü & Pante, 2018; Pineda et al., 2019). Chemical alteration changes the composition of the bone, influenced by agents such as fungi, microbial activity, gastric juices, or leaching of soluble elements in the sediment (Marchiafava et al., 1974; Piepenbrink, 1989; Fernández-Jalvo et al., 2002; Pineda et al., 2014). The chemical composition of the surrounding sediment and variables such as pH, moisture content, porosity and

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deposition time significantly affect bone preservation (Pate and Hutton, 1988; Nielsen-Marsh and Hedges, 2000; Smith et al., 2007).

These processes can cause additional wear or alter traces of human activity, hereafter referred to as 'manufacturing traces', making it difficult to accurately identify intentionally made marks in the archaeological record. This challenge arises because biostratinomic and diagenetic processes can alter human-made traces (e.g., Lyman 1994; Cook, 1986; Domínguez-Rodrigo et al., 2010; Pineda & Saladié, 2022; Rodríguez de la Fuente et al., 2024) or create pseudo-tools (e.g., Backwell and d' Errico, 2004, Backwell and d'Errico, 2008) from natural bones. For instance, studies have shown that bone surface roughness increases as weathering advances (Behrensmeyer, 1978; Vietti, 2016), which has a significant impact on the state of preservation of the bone cortical surface. Trampled bones may display striations that can overlap with pre-existing marks, such as cut marks, and potentially obscure or even erase previous surface modifications (Behrensmeyer et al., 1986; Olsen & Shipman, 1988; Gaudzinski-Windheuser et al., 2010). Flowing water can significantly alter the original morphology of bones (Shipman & Rose, 1983a, b; Behrensmeyer et al., 1989; Fernández-Jalvo & Andrews, 2003) and may even modify or obliterate human-made modifications (Shipman & Rose, 1983b; Behrensmeyer et al., 1989; Gümrükçu & Pante, 2018; Pineda et al., 2019; Pineda et al., 2023). Finally, the presence of water or damp environments can trigger processes such as the leaching of soluble elements from sediments. When soluble elements are leached, chemical reactions on bone surfaces can rapidly alter existing modifications (Pineda et al., 2014).

The presented preliminary research aimed to determine the impact of different sedimentary environments on the preservation of bone artifacts, with a particular focus on manufacturing traces. This included assessing how environmental factors may distort, alter, obliterate, or enlarge these traces, potentially leading to erroneous interpretations or omission of evidence. To achieve this, an experiment was conducted where specially prepared bone pieces with diverse manufacturing traces were deposited outdoors in five soil types for 3 and 6 years. While the duration of the deposition experiment was relatively short compared with fossil materials that have been in sediment for hundreds or thousands of years, the results provided numerous interesting observations and valuable information on the state of bone preservation. The study explores the scope and limitations of interpreting manufacturing traces on archaeological artifacts.

2. Materials and methods

Five randomly selected sediments from different locations in the central Polish Lowland (around the valleys of Lake Grodno and Lake Plebanka) were used, including soils common at archaeological sites: nonhumic sands, organic soil, and clay variants. Five sections with different soil types were prepared for sample deposition. Five square wooden frames (50 × 50 cm) were constructed and dug half a meter into the ground. Each section was filled with a different sediment type, each with a volume of approximately 0.125 m^3: loose, fine-grained sand; loose, various-grained sand with gravel; muck soil; loamy silt; and light clay. More detailed information about the soils used is presented in Table 1.

Five fresh red deer (*Cervus* elaphus) long bones (metapodials, cleaned of all soft tissues, including the periosteum) were used for experimental deposition. The bones were cut into similarly sized pieces (approximately 3 × 1.5 × 1 cm cuboids) using a diamond-coated rotary saw and placed in a water container until manufacturing traces were applied to their surfaces. To minimize variables, the same bone type and animal species (from a known origin) were selected, as interspecies differences in bone composition, density, and quality are suggested (e.g., Aerssens et al. 1998). The bones from red deer living in the same conditions – on a deer farm in Dąbrówka, Poland, were used. A total of 100 bone fragments were prepared. The number of samples was chosen to allow a statistical comparison of preservation between sediment types and deposition times. The surface of 50 fragments was scraped with a flint blade (longitudinal to the bone axis), while five short incisions were made on each of the remaining 50 fragments (transverse to the bone axis). Due to retouching the working edge of the flint tools, they were replaced with new specimens after 50 cuts and 20 scrapes, respectively. Both actions were performed by a single right-handed individual with similar force.

Table 1
Characteristics of soil types used in the experiment.

No	Type	Structure	Colour in state		pH	Content of $CaCO_3$
			dry	moist		
1	loose fine-grained sand	loose	2,5Y 6/3	2,5Y 4/3	7 (slightly alkaline)	little
2	loose, multi-grained sand with an admixture of gravel	loose	10YR 5/3	10YR 4/3	7 (neutral)	trace amounts
3	muck soil	grainy	10YR 2/2	10YR 2/1	4.5 (acidic)	absence
4	loamy silt	aggregate unstable (lumpy)	2,5Y 5/4	2,5Y 4/4	7,5 (alkaline)	a lot
5	light clay	subangular	10YR 6/4	10YR 4/4	6 (slightly acidic)	absence

Methods for determining properties: structure, granulation – organoleptic method; colour – according to the Munsell Atlas; pH – colorimetric method using a Hellige pH meter; $CaCO_3$ content – based on the reaction with 1 mol HCl.

A total of 20 bone fragments (10 with scraping marks and 10 with incisions), were placed in each section, with 5 samples of each type easily retrievable after each stage (Fig. 1). Finally, the bones were covered with a 2 cm layer of substrate. The samples were left in a natural environment, with the nearest trees, (a mix of conifers and deciduous species) 15 m away. The deposition area was fenced off. The experiment aimed to study how year-round weather cycles in Poland's temperate, continental climate affect the preservation and visibility of manufacturing traces on bones. Experimental samples were recovered after 3 (Stage I) and 6 years (Stage II), ensuring that excavation tools did not damage the cortical surface. Each bone fragment was packed in a perforated plastic string bag with a substantial label. Sediment and plant samples (from plants growing on the surface) were collected. After retrieval, the bone samples were cleaned in distilled water using an ultrasonic chamber for 4 min at 30 °C to remove substrate residues and dried at room temperature (approx. 20–24 °C).

Microscopic observation and photographic documentation of both manufacturing and post-depositional traces were carried out using low (<100 ×) and high magnifications (typically from 100 × to 500 ×). Studies on the state of preservation of the bone samples and the initial analysis of the manufacturing and post-depositional traces were performed using a Nikon SMZ-745 T microscope (up to 65 × magnification) fitted with a Delta Pix Invenio 6EIII camera. The measurements presented, such as the length and width of the various traces and the % of the eroded surface, were performed using DeltaPix InSight software and measured on the captured photos of the analyzed surfaces. This microscope also allowed to select the areas of interest that were later analyzed using a scanning electron microscope (SEM). The SEM analysis used an SEM/FIB Quanta 3D FEG with an LVSED detector and accelerating voltages ranging from 200 V to 30 kV. Equipped with a Schottky FEG thermal field emitter module, the SEM was operated at a spatial resolution of 1.2 nm in low vacuum mode (SE). The SEM was primarily used to investigate changes in the topography and texture of bone surfaces.

In order to fully comprehend the differences and similarities between the bone samples before and after each stage of the experiment,

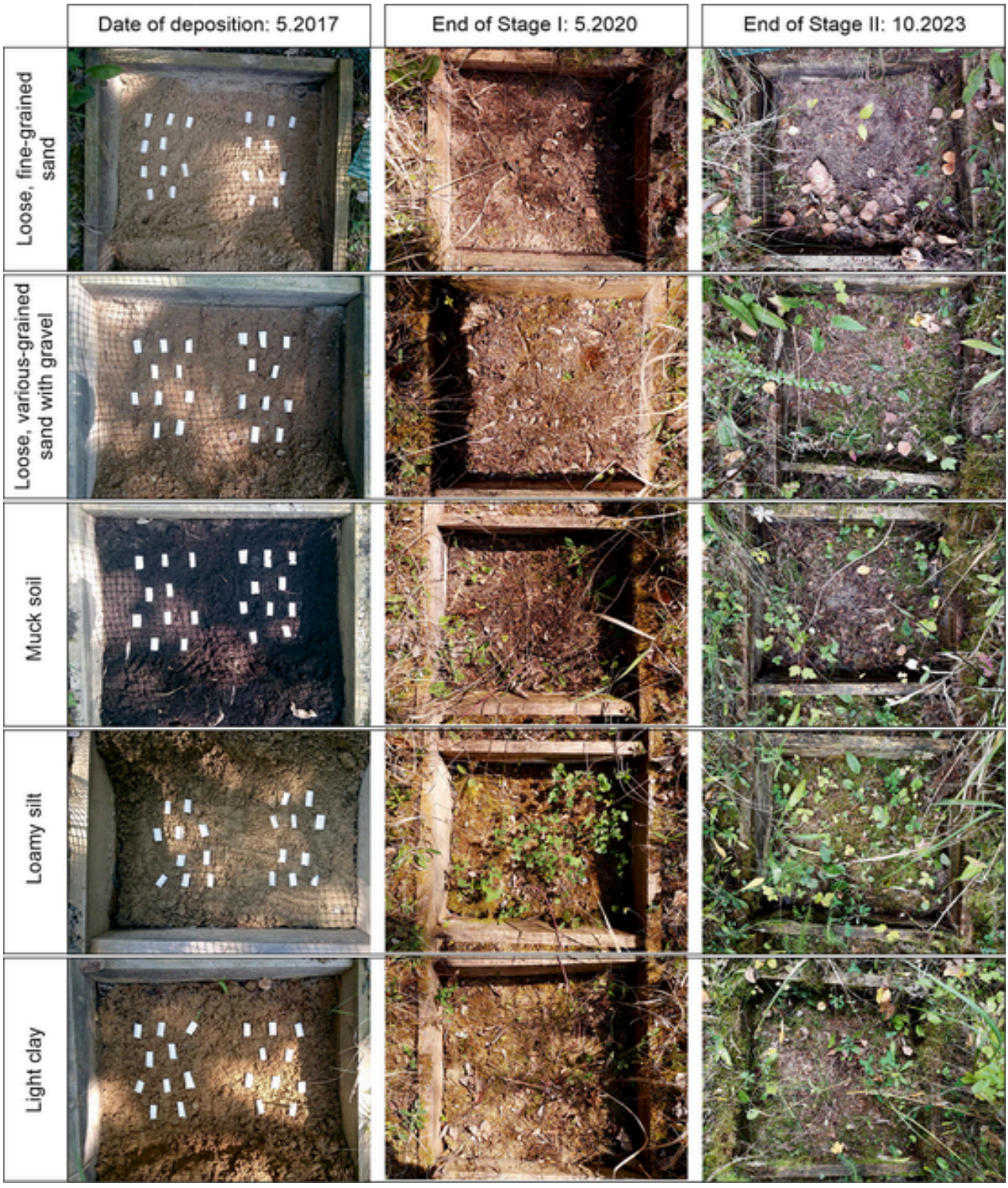

Fig. 1. General view of the experimental sections filled with various sediments before and after each deposition stage.

the manufacturing traces observed on their surfaces were characterized in detail at all stages of the experimental program (before deposition and after each stage).

The applied worked bone terminology in the context of bone samples is based on osteological nomenclature and studies in this respect known from the literature (e.g., Newcomer, 1974; Olsen, 1984; Évora, 2015; Orłowska, 2016). The taphonomical observations were made according to relevant literature concerning artifacts made of bone and antler (e.g., Fisher, 1995; Madgwick & Mulville, 2015; Fernandez-Jalvo & Andrews, 2016). Notably, these include potential changes which might have resulted from the influence of sediment in which the artifacts were deposited (Baxter, 2004; Senyane et al., 2023), as well as other potential alterations caused by plants and animals (e.g., Blumenschine et al., 1996; Montalvo, 2002; Macho-Callejo et al., 2023).

Table 2
List of plant species identified on the surface of given soil sections.

Type of soil	Identified plant species
Loose, fine-grained sand	red-stemmed feathermoss (*Pleurozium schreberi*)
Loose, various-grained sand with gravel	mouse-ear hawkweed (*Hieracium pilosella* L.), red-stemmed feathermoss (*Pleurozium schreberi*), rough goose neck moss (*Rhytidiadelphus triquetrus*)
Muck soil	white clover (*Trifolium* sp.), mouse-ear hawkweed (*Hieracium pilosella*), mnium (*Mnium* sp.)
Loamy silt	white clover (*Trifolium* sp.), mouse-ear hawkweed (*Hieracium pilosella*), rough goose neck moss (*Rhytidiadelphus triquetrus*), rough bluegrass (*Poa trivialis*)
Light clay	white clover (*Trifolium* sp.), mouse-ear hawkweed (*Hieracium pilosella*), seedling of a scots pine (*Pinus sylvestris*), red-stemmed feathermoss (*Pleurozium schreberi*), rough bluegrass (*Poa trivialis*)

3. Results

3.1. Plants identified on the surface of the sections

Soil type significantly influences potential vegetation. Plants develop their root systems in soil, from which they draw water and nutrients. Due to the diverse morphology of the soils used in the experiment (Table 1) and its duration, various small plants appeared on the surface of different sections (due to the natural dissemination of plants growing in the area surrounding the prepared experimental place). A complete list of identified plants can be found in Table 2.

On the surface of the section filled with loose, fine-grained sand, *Pleurozium schreberi* (red-stemmed feathermoss) appeared in many places. In the section with loose, variably grained sand and gravel, *P. schreberi*, *Hieracium pilosella L.* (mouse-ear hawkweed), and *Rhytidiadelphus triquetrus* (rough gooseneck moss) were present. *Trifolium* (clover), *H. pilosella*, and *Mnium* mosses were observed in the muck soil section. The loamy silt section was abundantly covered with *Trifolium*, *H. pilosella*, and *R. triquetrus*. Moreover, the light clay section featured species such as *Trifolium*, *H. pilosella*, a single *Pinus sylvestris* (pine seedling), and *P. schreberi*.

3.2. Results of the microscopic studies

3.2.1. Characterization of the bone surface prior to deposition

Prior to deposition, the surfaces of the samples exhibited the hallmark characteristics of natural cortical bone: smooth, dense topography and an off-white to pale yellowish hue. Samples with scraping marks from a flint blade, showed long, straight striations (Fig. 2a, b), either parallel or intersecting, often arranged in bands. These bands consist of shallow, parallel scratches with a similar depth and a generally V- or U-shaped cross-section. Gentle streaks or groove-like marks are visible between these sets of linear marks. In turn, the incisions made on the remaining samples are generally linear or slightly curved, with a V-shaped profile and asymmetrical cross-section (Fig. 2c, d). The walls and bottom of each mark display microstriations—parallel lines running along the length of the mark.

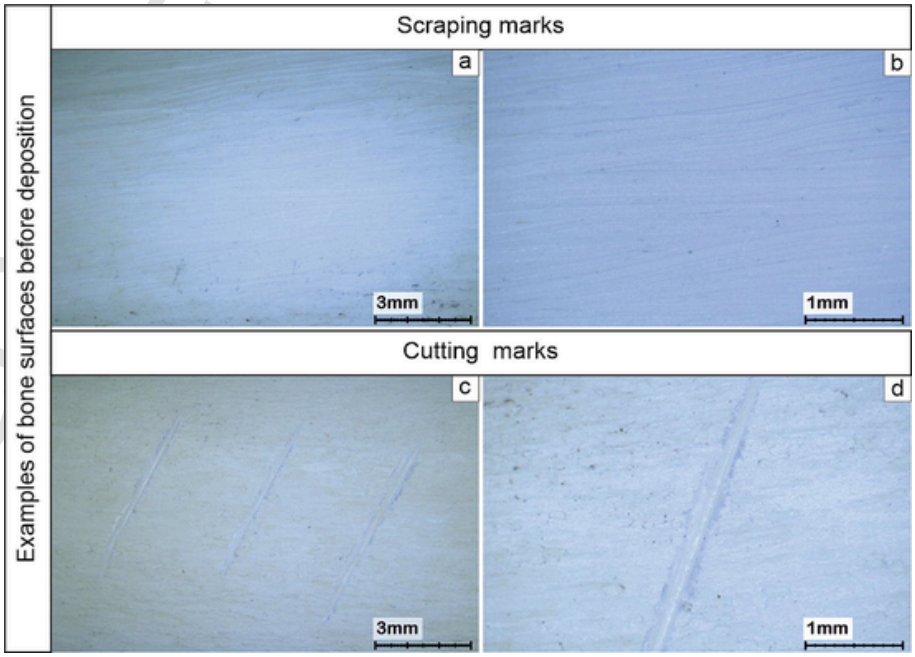

Fig. 2. Examples of manufacturing traces made by flint tools on the cortical surfaces of experimental bone samples before deposition: a, b – scraping marks; c, d – incisions.

3.2.2. Characterization of the bone surface after deposition

Microscopic analysis showed diverse changes in bone samples deposited in different soils and for varying periods. The changes are particularly interesting as they occurred naturally over a known period under observed conditions. Detailed data on these changes are provided in the Supplementary Material (Supplementary Table 1).

3.2.2.1. Bone samples deposited in loose, fine-grained sand. Irregular light to dark brown patches were observed on most bone fragments in this section, accompanied by small, grouped dark spots. In bones collected after 3 years, these spots appeared as discoloration and shallow depressions in the cortical layer (Fig. 3a-c, i-k). However, in samples recovered after 6 years of deposition, the spots started to erode the surface of the bone intensively, leading to the destruction of its outer layers, similar to an exfoliation effect (Fig. 3e–g, m-o). The bone within and at the base of these patches had a rough, often fibrous and cracked appearance (Fig. 3d, g, h).

These changes significantly impacted the preservation of manufacturing traces on the bones. Scraping marks were well preserved in areas unaffected by erosion (Fig. 3b) but almost destroyed and unreadable in eroded areas. This was particularly noticeable in samples obtained after 6 years of deposition (Fig. 3f, g, h). On the 3-year samples, where only a darker discoloration occurred, the readability of the marks was still good (Fig. 3c). A similar situation occurred with the cuts. Early erosion with color changes left surfaces legible (Fig. 3i–k)), but as microexfoliation affected the incisions, erosion set in (Fig. 3l-o). This changed the shape of the incision and caused internal erosion and micro-cracks along the marks. This is particularly evident in the scanning electron microscope (SEM) images (Fig. 3p). In many cases, the erosion was so deep that it completely or partially destroyed the incisions, making their contours unreadable (Fig. 3n). On most samples with an eroded cortical layer, bone histological traits, such as the Haversian system and lamellae, were exposed. Additionally, cracks were observed, often associated with areas where nutrient foramina were present. These cracks ran along the axis of the bone and occasionally crossed the manufacturing traces (Fig. 3g, n, o, p).

3.2.2.2. Bone samples deposited in loose, various-grained sand with gravel. The changes observed on the surface of the bones from the section discussed are almost identical to those observed on samples deposited in loose, fine-grained sand. Again, there are light to dark brown patches of irregular shape and size (Fig. 4a, b, i, l), the invasiveness of which increases with time, resulting in a patchy or more concentrated flaking and exfoliation effect (Fig. 4e, f, h, m, n, p). The darker areas contrast sharply with the unaffected cream-colored bone (Fig. 4b, i). In a few cases, bones dug up after 6 years of burial were almost entirely covered by erosion (Fig. 4f, m). Extremely severe surface cracking was observed in these samples (Fig. 4f, g, n, p). These changes have had a significant impact on the preservation of manufacturing traces, causing them to be wholly eroded and illegible in some areas (Fig. 4f, k, n) or altered to such an extent that they deviate significantly from their original shape (Fig. 4j, o). On most samples with an eroded cortical layer,

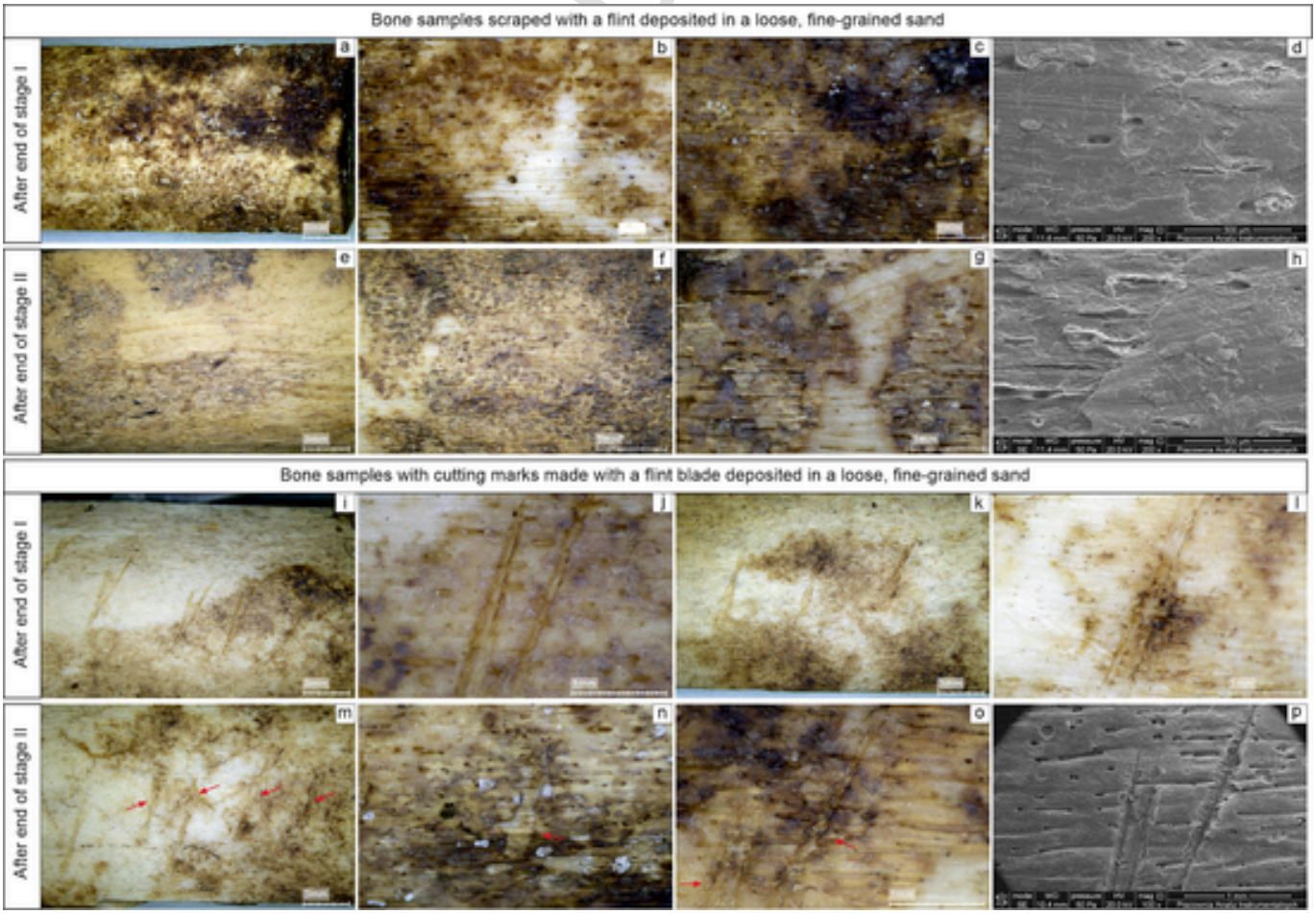

Fig. 3. The taphonomic modifications observed on the cortical surface of scraped and incised bone samples deposited in loose, fine-grained sand after Stage I and Stage II of deposition. Changes were documented under light (a-c, e-g, i-o) and scanning electron microscopy (d, h, p).

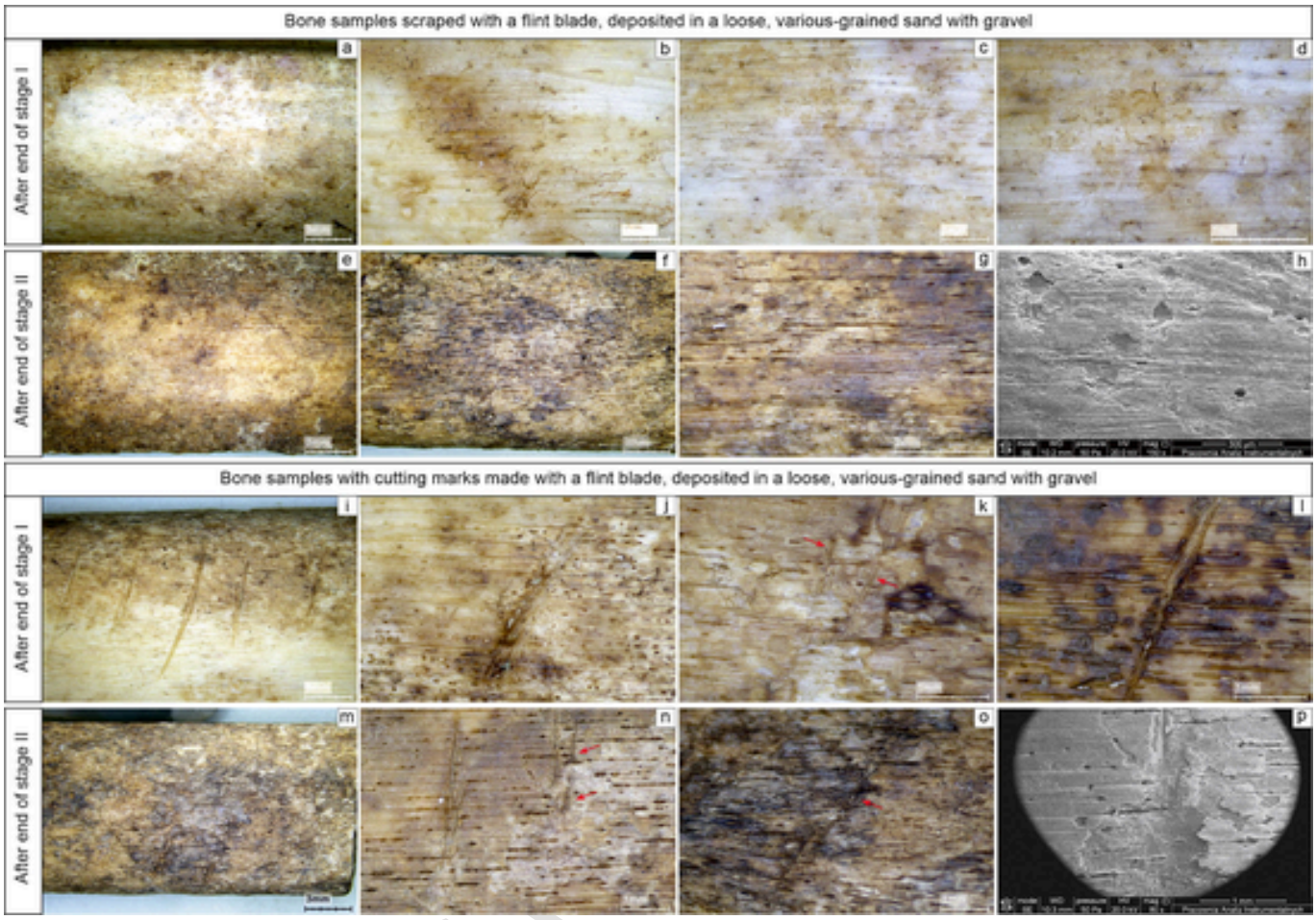

Fig. 4. The taphonomic modifications observed on the cortical surface of scraped and incised bone samples deposited in loose, various-grained sand with gravel after Stage I and Stage II of deposition. Changes were documented under light (a-g, i-o) and scanning electron microscopy (h, p).

histological traits such as the Haversian system and lamellae were exposed.

3.2.2.3. Bone samples deposited in muck soil. The condition of the bone fragments in this case was significantly better than in the previously described depositional contexts. The most noticeable change was a shift to various shades of brown (Fig. 5). In addition, dark, localized discoloration appeared on the singular bones in the form of more or less circular or oval pits no larger than 0.5 mm in diameter (Fig. 5f, g). In general, these discolorations were similar to those described previously. Over time, as the bone darkened, a pitting effect developed on the previously darkened pits, resulting in localized exfoliation of the bone surface (Fig. 5g, h). However, such invasive erosion occurred in only two cases (after 6 years of burial). Manufacturing traces were well preserved in most cases, with changes primarily associated with the dark, localized discoloration effect. In addition, cracking was noticeable more frequently on samples deposited in soil for 6 years. In many cases, the observed cracks disrupted the continuity of the incisions (Fig. 5g, h, n-p).

3.2.2.4. Bone samples deposited in loamy silt. In this case, the changes observed on the surface were slightly different. The color of the bones varied; some retained their natural off-white to pale yellowish hue (Fig. 6a, i). The changes observed in the samples deposited for 3 years were, at first glance, minimally invasive (Fig. 6c, d). Individual darker discolorations of varying sizes were noted (Fig. 6b, j), but they did not cover large areas of the bone surface and had minimal effect on the manufacturing traces. Additionally, characteristic isolated U-shaped furrows with a slightly meandering or branching pattern were observed (Fig. 6f, g, k, i). These visible marks were generally thin (not exceeding 500 μm) and varied in curvature, length, and width. The interiors of these marks had a corroded appearance (Fig. 6k). In a few cases, these U-marks intersected both linear bands associated with scraping and incisions, which was the primary form of erosion in this case (Fig. 6 k, l). Delicate cracks on the bone surface were noted (Fig. 6k).

However, the damage was considerably more severe in the samples collected after 6 years. The bones had become almost uniformly cream or light brownish-yellow in color (Fig. 6e, h, m, n). Erosion associated with dark discoloration and U-marks was considerably more invasive (Fig. 6h, o). Larger fragments of the bone surface were significantly eroded, almost completely obscuring the manufacturing marks, whether scraped (Fig. 6h) or incised (Fig. 6n, o). The U-shaped marks covered large areas of the bone, with overlapping and intersecting manufacturing traces clearly visible (Fig. 6f, g, n-p). Cracking of the bone surface was also noted in many places (Fig. 6o, p).

3.2.2.5. Bone samples deposited in light clay. The changes observed in this group are similar to those evident in samples deposited in loamy silt. In samples recovered after 3 years, the bones retained their off-white to pale yellowish hue (Fig. 7a–c), although some areas showed a slight yellow–brown discoloration. These discolorations often took on

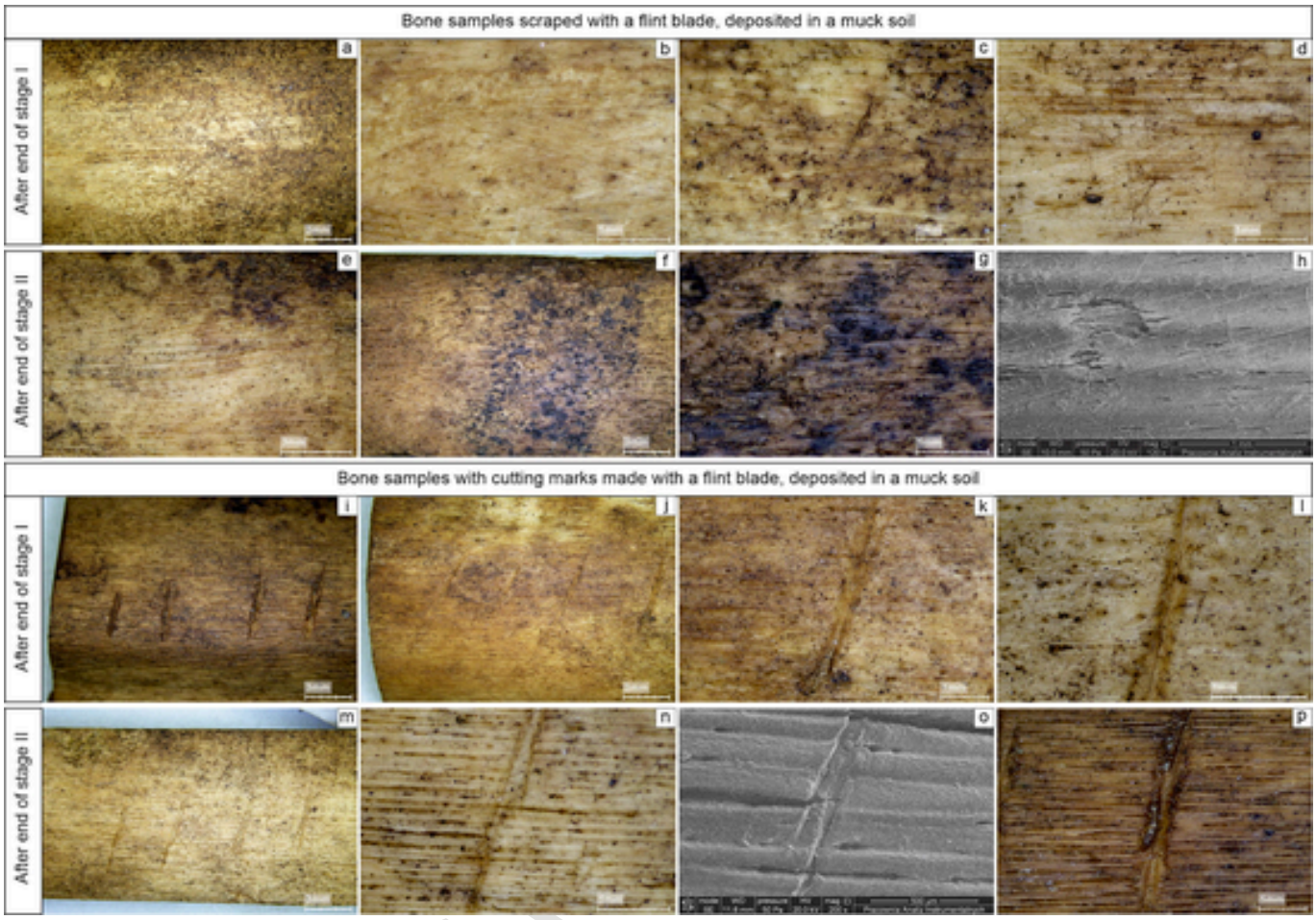

Fig. 5. The taphonomic modifications observed on the cortical surface of scraped and incised bone samples deposited in a muck soil after Stage I and Stage II of deposition. Changes were documented under light (a-g, i-n, p) and scanning electron microscopy (o).

a slightly rounded (Fig. 7c) or U-shaped meandering pattern (Fig. 7d, i, j), subtly eroding the original surface of the bones (Fig. 7j, l). This was the main factor locally affecting the manufacturing traces.

In contrast, samples recovered after 6 years, showed marked variation in the intensity of the changes to the bone surface, closely related to discoloration and U-shaped marks (Fig. 7e-h, m-p). Areas without these changes showed good preservation despite the passage of time (Fig. 7e, f). The most significant changes in the marks and their erosion occurred within the darkest discolorations, connected often with U-shaped meandering furrows and associated areas affected by bone exfoliation and flaking (Fig. 7f-h, n-p). In addition, cracking was evident, affecting the continuity of linear traces associated with scraping (Fig. 7h) and single incisions (Fig. 7p). On most samples with an eroded cortical layer, histological traits such as the Haversian system and lamellae, were exposed.

4. Discussion

In contrast with the prevailing approach to microscopic analysis of bone tools (e.g., Olsen, 1984; LeMoine, 1994; Orłowska, 2016; Orłowska et al., 2022), this study focused on the impact of post-depositional alterations on the preservation of traces. The objective was to determine whether a relatively short deposition period (3–6 years) affects the preservation and visibility of manufacturing marks on bone artifacts. This time interval, though shorter than 10 years, is comparable to many other taphonomic experimental burial periods tested by various researchers (e.g., Armour-Chelu and Andrews, 1994; Denys, 2002; Howes et al., 2012; Krajcarz, 2017; Orłowska, 2018; Pollock et al. 2018; Gutiérrez, 2021; Macho-Callejo et al., 2023) and was sufficient to produce surface modifications such as changes in color, roughness, cracking, and root marks affecting the bone cortex. Bone preservation, both short-term and long-term, depends on a complex array of factors, including intrinsic bone properties, plant and microbial activity, temperature, soil mineral composition, and soil pH (Child 1995; Hedges et al., 1995; Henderson, 1987; Nielsen-Marsh & Hedges, 2000). The diverse deposits in which bone artifacts were found demonstrate the varied impacts on bone preservation, with bones in this study showing clear evidence of multidirectional deformation. The condition of the bones after each experimental deposition period can be described as dry. The primary differences are macroscopic, manifesting as changes in color and general surface erosion. The microscopic level shows the surface modifications in detail.

The first notable change in the examined samples was coloration, appearing as either (1) general bone discoloration or (2) localized discoloration linked to erosion. The most uniform change was seen in samples deposited in muck soil, clearly visible after just 3 years. In the case of other sediment types, discoloration intensity increased with extended deposition periods (Fig. 9:A). This was observed in samples retrieved after 6 years from light clay and loamy silt. Bones frequently absorb the color of their surrounding medium due to their porous, wicking structure and naturally pale coloration. This absorption can result in specific stains from various mineral deposits, such as iron and copper

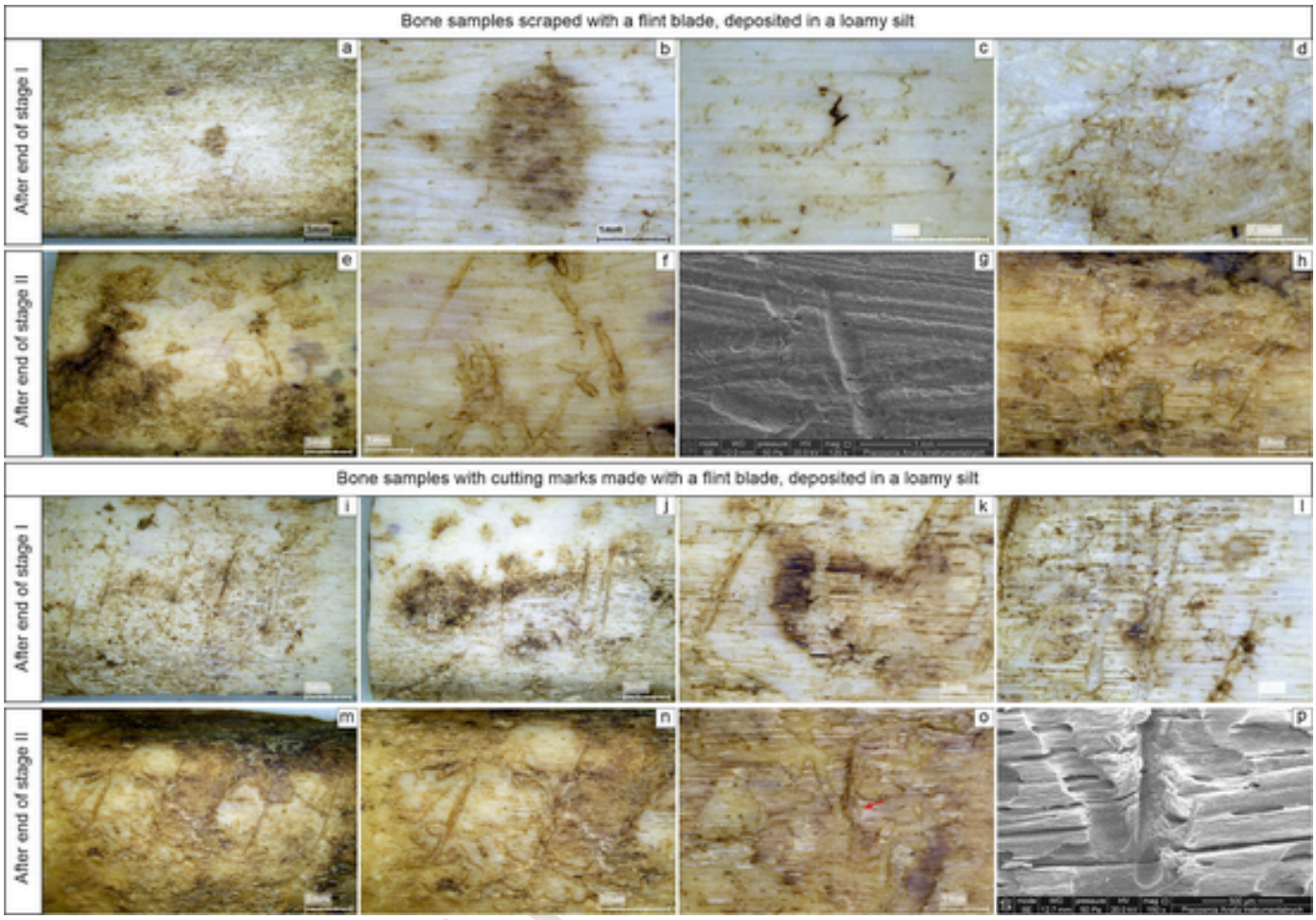

Fig. 6. The taphonomic modifications observed on the cortical surface of scraped and incised bone samples deposited in a loamy silt after Stage I and Stage II of deposition. Changes were documented under light (a-f, h-o) and scanning electron microscopy (g, p).

oxides, as well as organic compounds, particularly tannins (Barbehenn and Peter Constabel, 2011; Pollock et al. 2018). A change in the color can be associated, among others, with different kinds of enzymes present in plants and many chemical catalyzations that occur in the soil when plant material degrades (Painter, 1991a, 1991b; Dupras & Schultz, 2014; Pollock et al. 2018). Notably, the scraped bone surfaces exhibited less discoloration than the natural cortical bone surfaces. This reduced discoloration can be attributed to the lower porosity of the scraped areas, making them less susceptible to absorbing tannins and other staining agents in the soil (compare, for example, Orłowska 2018).

In the second case (2 – localized discoloration), the effect is mainly caused by moss rhizoids (anchoring structures, superficially root-like but without the absorptive functions of true roots) and plant roots, which may stain bones dark brown and black (Fernández-Jalvo & Andrews, 2016, 158). Notably, bones are a potential source of highly concentrated nutrients for plants, mainly due to their nitrogen (N) and phosphate (PO43−) content (Pokines & Baker 2014). In the analyzed bone fragments, many signs of observed damage suggest that plants were responsible for most of the observed erosion. The roots of small plants and rhizoids can extend into bones buried near the surface. The samples were covered by a relatively thin, 2 cm layer of sediment, likely facilitating contact between these agents and the bones (Fig. 8a, b). This was evident during the excavation of samples in loamy silt and light clay, where white clover (*Trifolium* sp.) roots and moss rhizoids formed a dense structure with the soil (Fig. 8c–e), or moss directly covered partially exposed bone fragments (Fig. 8f, g). Multiple researchers have noted that the symbiotic association of fungi (mycorrhiza) or bacteria (rhizobia) with roots or the decomposition of the roots themselves may produce acidic compounds likely responsible for most bone damage (Grayson et al., 1988; Lyman, 1994, 375; Domínguez-Rodrigo & Barba, 2006; Pesquero et al., 2018). On some samples, "fluffy" white hyphae of mycorrhizal fungi, associated with roots of white clover, were observed (Fig. 8n). Notably, this association was primarily responsible for the dark, localized discolorations that appeared on the bone surfaces in the form of more or less circular or oval pits (i.e. Fig. 8o; Fig. 9:B), which were responsible for the localized exfoliation of the bone surface in most of the cases (Fig. 8p; Fig. 9:E). The mentioned hyphae, thread-like structures characteristic of many molds, can invade the porous structure of bone and cause focal damage (Jans et al., 2002). This results in a rough, eroded surface through acidic dissolution, similar to the effects of acidic soil corrosion on bone minerals. However, the evidence suggests that fungal damage often results in more localized patches of erosion with irregular edges (Armour-Chelu & Andrews, 1996; Nicholson, 1996, 1998). Moreover, on bones with an eroded cortical layer, histological traits, such as the Haversian system and lamellae were exposed. This phenomenon was identified in numerous analyzed samples (Fig. 8r; Fig. 9:C; compare Supplementary Table 1).

Surfaces affected by so-called root etching exhibited well-defined U-shaped furrows that often branched out which invasively eroded the observed surfaces. SEM images revealed that the roots, among others, created U-shaped depressions in the bone and penetrated its pores and

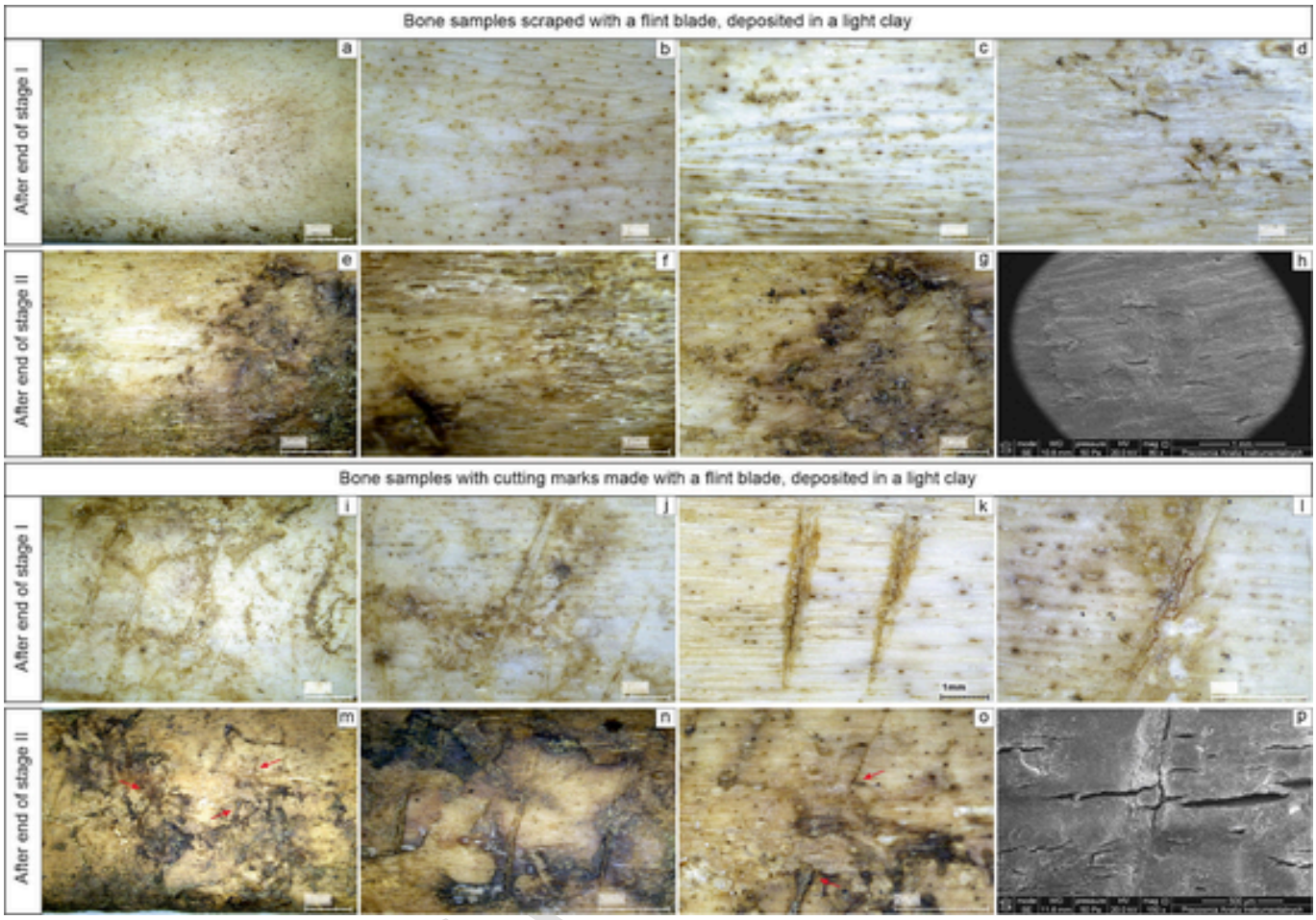

Fig. 7. The taphonomic modifications observed on the cortical surface of scraped and incised bone samples deposited in a light clay after Stage I and Stage II of deposition. Changes were documented under light (a-g, i-o) and scanning electron microscopy (h, p).

cracks (Fig. 8h, i). Most of the mentioned furrows were observed on bone samples deposited in loamy silt and light clay (Fig. 9:D). Importantly, these furrows were most likely formed by the roots of white clover (*Trifolium* sp.), mouse-ear hawkweed (*H. pilosella*) and rough bluegrass (*Poa trivialis*), as these were the most invasive plants on the surface, in addition to various mosses (compare Table 2). Root marks can start to affect the bone cortex as early as 1 year after exposure, with more pronounced features observed in bones exposed for extended periods (up to 10 years) (Macho-Callejo et al., 2023). Plant roots often destroy bone, leaving behind a pattern of surface damage in the cortical bone known as root etching (Andrews & Cook, 1985; Fig. 8l, m). This damage is likely caused by the exudation of weak acids by plant roots, which may increase the availability of phosphates in the bones for absorption (Micozzi, 1991; Davis, 1993; Walker et al., 2003; Gifford-Gonzalez, 2018). The cross-sectional width of these root marks is often wider than the size of the actual root, making it challenging to identify the specific plants responsible for the marks. However, such attempts are being made (e.g., Macho-Callejo et al., 2023). The fungi or bacteria that cover smaller or secondary roots and filaments (root hair or rhizoids) extend laterally into the bone and dissolve it forming the root mark (Fernández-Jalvo & Andrews, 2016, 33). In the case of the presented research, roots of small plants and filaments had a significant contact with the cortical layer of most of the analyzed bones. These roots frequently penetrated the manufacturing traces, as evident, for example, in the case of incisions (Fig. 7l; Fig. 8j, k), where such networks of filaments started eroding them from the inside, causing a change in their original morphology. This was likely influenced by the aforementioned exudation of weak acids. This, in turn, resulted in the deformation of selected marks, manifesting as slight unevenness of the edges of the incisions and larger distortions due to the formation of U-shaped furrows made by roots.

To gain an accurate understanding of the erosion observed on the samples, it is essential to consider the type of sediment in which the sample was deposited. Two types of sand were used in the experiment. These consisted of loose fine-grained sand and loose, various-grained sand with an admixture of gravel. Both sediments are built by particles that are not well compacted or bound together, leading to a structure that is easily disrupted by water, wind, or physical disturbance (Brady 1984, 36-42). The high permeability of loose sand can result in the leaching of minerals, such as calcium and phosphate, from the bone, thereby accelerating its degradation (Pineda et al., 2019; Pineda & Saladié, 2022). In the analyzed samples, deposited in these soils, numerous cracks had formed, and the bones had undergone desiccation. This could be attributed, at least in part, to the properties of the sands. In contrast, muck soil, has a high water-holding capacity due to its fine particles and high organic content (Brady 1984, 481-488). In contrast to the sandy soils previously described, muck soil is characterized by poor drainage due to its fine texture and high water retention. Such conditions may result in anaerobic environments, particularly in waterlogged areas, which can limit root growth and microbial activity, ultimately affecting plant growth. This may explain why erosion related to root activity (localized dark spots) was identified in only one bone sam-

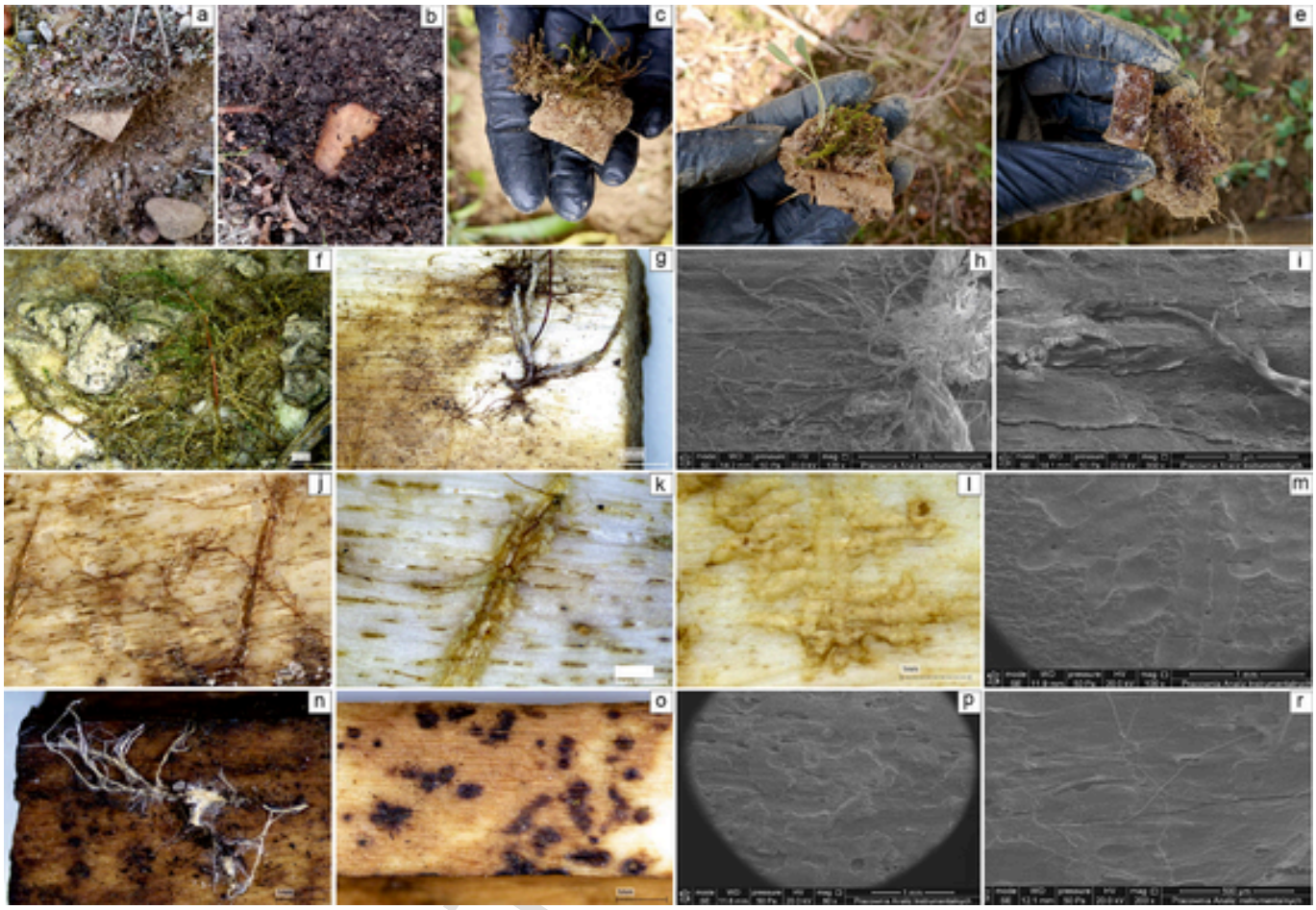

Fig. 8. Illustrative photos of bone samples during excavation: a-loose various grained sand with gravel; b- muck soil; c- loamy silt; d, e – light clay; and examples of factors responsible for their erosion: f, g – moss rhizoids; h, i – SEM images showing erosion of the cortical layer caused by moss rhizoids on bones deposited for 6 years in light clay; j – moss rhizoid network covering a bone retrieved after 3 years from loamy silt; k – internal penetration of a cut mark by moss rhizoids; l – U-shaped linear marks made by roots on a bone surface after 3 years of deposition in loamy silt; m – SEM image of U-shaped linear marks from roots on bone deposited in loamy silt; n – symbiotic fungus-root association (mycorrhiza) on a white clover (*Trifolium* sp.) root identified on a bone from muck soil; o – bone sample deposited in a muck soil showing dark spots linked to mycorrhiza; p – SEM image of eroded surface with dark spots on bone (muck soil, after 6 years of deposition); r – SEM image of eroded cortical bone exposing histological features like the Haversian system and lamellae (loamy silt, after 6 year deposition).

ple after 3 years, and two samples after 6 years, despite the presence of individual plants on the surface. The final two types of soil used in the experiment, loamy silt and light clay, contain a significant proportion of clay along with considerable amounts of sand or silt, making them less dense and heavier than pure clay soils. The soil particles in loamy silt and light clay soils are relatively small, which allows them to hold together effectively. This soil type can retain a substantial quantity of water due to the tight binding of the clay particles to water molecules, thereby conferring greater drought resistance than sandy soils (Brady 1984, 36-42). Both described soils are typically fertile, which is beneficial for root growth and microbial activity, and they have a good balance of moisture retention and drainage. This is because the nutrients are less susceptible to leaching compared to sandy soils, making them more readily available to plants. The fine particles retain nutrients and water, while the sand or silt content facilitates root penetration to a greater extent. The characteristics of both soils, supported a richer variety of vegetation in the experimental sections, including mosses, white clover (*Trifolium* sp.), rough bluegrass (*P. trivialis*), and mouse-ear hawkweed (*H. pilosella*). This effect was observed in the bone samples analyzed, where the presence of well-defined U-shaped furrows evidenced the invasive interference of the roots, which were more pronounced and numerous than in the other used soil types.

Another significant factor is the general chemical composition of the surrounding sediment and its pH. Bone preservation is typically excellent in depositional environments with near-neutral or slightly basic pH. It is assumed that the most pervasive long-term destructive force acting upon bones is soil acidity (Casallas & Moore, 2012; Crow, 2008). Bone deposition in humid, acidic environments can result in changes in the organic matter that comprises these bones; for example, loss of minerals manifested in shrinking, cracking, and surface erosion (Nicholson, 1996; Turner-Walker and Peacock, 2008). A similar effect can be observed on experimental bone samples deposited in muck soil presented in this study, which had an acidic pH of 4.5, and light clay with a slightly acidic pH of 6. Bone fragments deposited in these sediments exhibited significantly more invasive cracking on surfaces than other samples, which was well shown by the SEM imaging of analyzed surfaces (Fig. 9:F). Notably, most observed cracks had a characteristic torn-like appearance (Fig. 5h, o; Fig. 7p), which is diagnostic of corrosion caused by an acidic environment.

In addition to those mentioned, significant factor was undoubtedly the deposition duration. Analysis of the degree of surface erosion of the experimental samples clearly showed that over time, erosion intensified (Fig. 9:E, F; Fig. 10.; Supplementary Table 1). This effect was observed in bones deposited in both types of sands, loamy silt and light clay. The

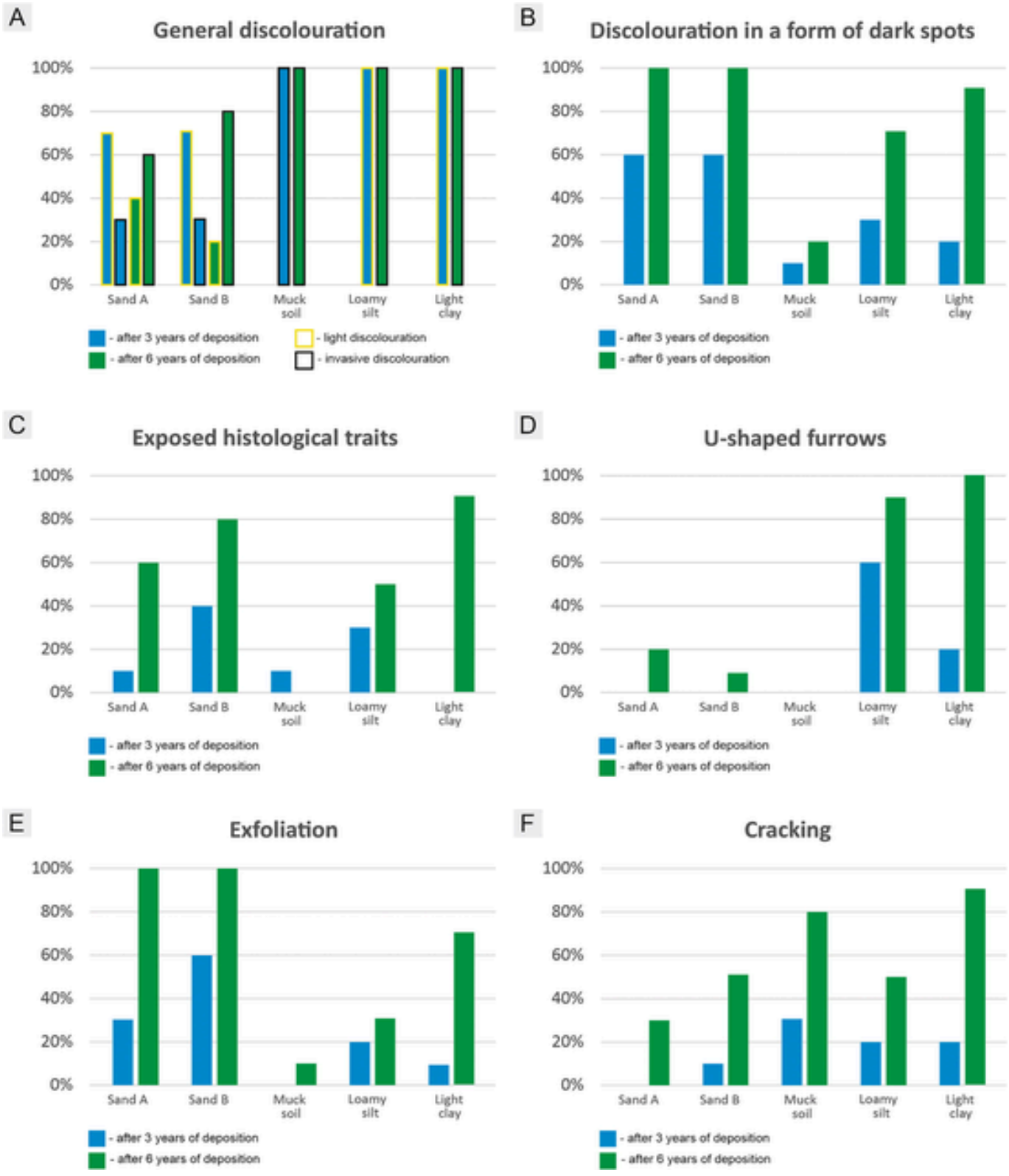

Fig. 9. A graphical representation of the main results of this study. The raw data are presented in Supplementary Table 1.

only consistent state of preservation was noted in muck soil, where invasive erosion did not occur, and only minor changes, such as small cracks, were observed. In contrast, the most significant number of samples with unreadable or poorly preserved manufacturing traces (< 25 % of the original surface) were found in loose, various-grained sand with gravel, and after a 6-year deposition in light clay.

In response to the question posed in the title, "How much did we lose?" the presented preliminary experimental research demonstrated

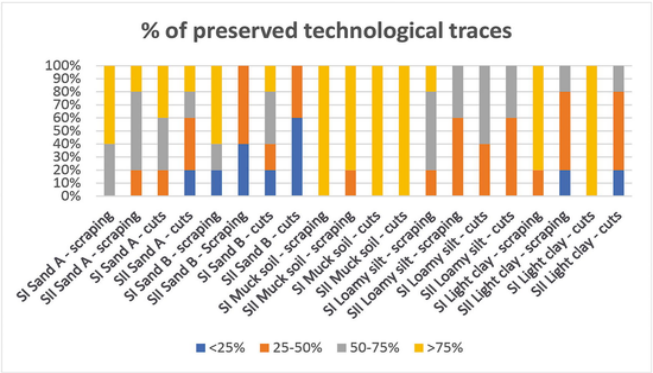

Fig. 10. Diagram showing the % of preserved manufacturing traces on each type of bone samples.

the highly destructive impact that depositional contexts can have on bone preservation, even during the relatively short deposition time. As detailed in the results section of the article, post-depositional factors can distort and completely obliterate manufacturing traces. The findings from the presented experiment unequivocally show that the data we can gain from specific artifacts are often heavily dependent on the post-depositional conditions they have endured, and the potential scope and limitations of interpreting manufacturing traces recorded on archaeological artifacts are directly connected with this matter.

5. Conclusions and outlook

In conclusion, this research has given valuable insights into how different sediments affect the preservation of manufacturing traces and the condition of bone samples over time. The experimental results offer information on the specific traits characteristic of each depositional environment and surface modifications that are diagnostic for particular agents and processes. Results revealed differences in the intensity of bone degradation related to the erosion made by different plant roots and filaments often associated with mycorrhizal fungi. Due to the specific characteristics of the sediments used and the unique diagenetic processes observed, the findings from this study are preliminary and should, at this stage, be considered relevant only to the conditions described in the experiment. Nevertheless, these observations are significant and contribute to our understanding of how various post-depositional factors affect artifacts made from osseous materials and bones in general. The examination of the influence of the depositional environment on bone artifacts (and associated factors) through experimental and traceological studies offers invaluable insights into the transformation of archaeological materials over time. Such insights facilitate researchers' comprehension of the taphonomic processes at play and enable a better interpretation of past human societies' cultural and manufacturing practices.

Further investigation is required to elucidate the mechanisms underlying bone preservation. This should encompass extended durations, varying deposition depths, and a thorough analysis of all potential factors influencing bone preservation. Therefore, the next step should be a detailed histological and chemical analysis of the bones and the sediments used. In the future, these results serve as a valuable reference point for comparative analyses with archaeological materials, thereby enhancing our understanding of how depositional environments influence the interpretation of artifacts and the human made traces on their surfaces. Furthermore, the presented findings may be helpful in forensic science research.

Uncited references

CRediT authorship contribution statement

Justyna Orłowska: Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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Declaration of competing interest

The author declare that she have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2024.104863.

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